



## Energy and $X_{max}$ reconstruction of hadron-initiated showers in surface arrays

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**Abstract:** The current methods to determine the primary energy in surface arrays are different when dealing with hadron or photon initiated showers. In this work, we adapt a method previously developed for photon-initiated showers to hadron primaries. We determine the Monte Carlo parametrizations that relate the surface energy estimator and the maximum of shower development for both, proton and Iron primaries. Using for each primary their own set of calibration curves, which is of course impossible in practice, we show that the energy could be inferred with a negligible bias and 12% resolution. However, we show that a *mixed* calibration could also be performed, including both type of primaries, such that the bias still remains low and the achieved resolution is around 15%. In addition, the method allows the simultaneous determination of  $X_{max}$  in pure surface arrays with resolution better than 7%.

**Keywords:** Energy,  $X_{max}$ , surface detectors

## 1 Introduction

In large ultra-high energy cosmic ray surface arrays the technique traditionally used to determine the primary energy consists on the inference of the lateral distribution of particles of the extensive air shower (EAS) it produces into the atmosphere. Scintillators (e.g., Volcano Ranch, AGASA, KASCADE) and water Cherenkov detectors (e.g., Haverah Park) have been mainly used for this purpose. The surface array allows the discrete sampling of the shower front at ground level and then, the lateral distribution is fitted assuming a certain functional form (LDF, lateral distribution function). Later, the signal inferred at an optimum distance is used as the energy estimator, which is related to the primary energy using Monte Carlo (MC) parametrizations. This optimum distance is traditionally fixed for each experiment since it is assumed to be only dependent on the array spacing. However, recent studies suggest the convenience of calculating the optimum distance for each individual shower taking into account primary energy and direction [2]. A special case from the experimental point of view is the Pierre Auger Observatory which pioneers the simultaneous use of water Cherenkov detectors and fluorescence telescopes. For these *hybrid* events, systematic errors in their energy estimate are greatly reduced [3].

These methods assume that primary is a proton and it is considered adequate for heavier primaries since the estimated energy for nuclei depends weakly on their mass number. On the other hand, the difference is signifi-

cant when dealing with photon-initiated showers since the muonic component is much lower, shower development is affected by the geomagnetic field and the LPM effect delays in average the first interaction. Thus, each experiment has followed a different method when searching for photon primaries. Haverah Park and Auger use the muon density at ground [4] and MC parametrizations [5] to infer the primary energy respectively, while in [6, 7], AGASA data is directly compared to photon MC simulations.

The method used by Auger [5] was first proposed in [1]. The original idea was to adapt the energy reconstruction method to the late development of photon showers and the key point is to rely explicitly on the development stage of the shower. The method was originally applied to photon showers in an Auger-like array. An empirical parametrization between  $S(1000)/E$  and  $\Delta X = X_{ground}/\cos\theta - X_{max}$  was found, where  $S(1000)$  is the inferred signal at 1000 meters from the shower axis,  $E$  is the primary energy,  $X_{max}$  is the maximum of shower development and  $\theta$  is the zenith angle of the shower. The parametrization is almost independent of the primary energy due to the well-known universality of the electromagnetic component of EAS [8, 9, 10] and the small muon fraction in the photon-initiated showers.

In this work, we show how to modify this method to be applicable to hadron-initiated showers where the muon component is significant, specially, in case of water Cherenkov arrays which enhanced their contribution to the total measured signal. In this way it is possible to determine simul-

taneously the energy and  $X_{max}$  of the shower from pure surface data. Alternatively, several surface parameters have been used to infer indirectly  $X_{max}$ , such as the rise time of the signals in the detectors and the azimuthal features of the time distributions [11].

## 2 Simulations

The simulation of the atmospheric showers is performed with the AIRES Monte Carlo program (version 2.8.4a) [12] using QGSJET-II-03 as the hadronic interaction model (HIM). The input primary energy goes from  $\log(E/\text{eV}) = 19.0$  to  $19.6$  in  $0.1$  steps. Around 300 events have been simulated per each energy and for both, proton and iron primaries. The zenith angle has been selected following a sine-cosine distribution from  $30$  to  $60$  degrees, while the azimuth angle is randomly distributed.

As it will be explained in Section 3, only the reconstructed  $S(1000)$  and zenith angle of the shower will be needed in the method proposed here. We simulate the reconstructed zenith angle by fluctuating the real one with a Gaussian whose standard deviation is  $1^\circ$ , a typical value of its uncertainty in surface arrays [13, 14, 15, 16].

A realistic  $S(1000)$  of the event could be obtained from

$$\begin{aligned} E &= A(S_{38})^B \\ S(1000)(\theta) &= S_{38} \times [1 + Cx - Dx^2] \end{aligned} \quad (1)$$

where  $x = \cos^2(\theta) - \cos^2(38^\circ)$ .  $A$ ,  $B$ ,  $C$  and  $D$  are constants obtained in [17] for QGSJET-II-03 and for iron and proton primaries. However, event by event fluctuations and reconstruction uncertainties are not taken into account if  $S(1000)$  is directly estimated from Eq. (1). Thus, we calculate the reconstructed  $S(1000)$  from our own simulation of the detector response and reconstruction process, as it is explained next.

The simulation of the tank response and the fit of the LDF are performed using our own simulation program previously tested in [2]. An infinite array whose unitary cell consists on a triangle with detectors separated  $1.5$  km is considered. The real core is randomly located inside an elementary cell and the reconstructed one is determined fluctuating the real one with a Gaussian function whose standard deviation depends on the primary energy and composition (more details en [2]).

The signal collected at each station for a given shower with a certain energy and zenith angle is set assuming a *true* lateral distribution function like [17]

$$S(r) = S(1000) \times \left(\frac{r}{1000}\right)^{-\beta} \times \left(\frac{r+700}{1000+700}\right)^{-\beta}, \quad (2)$$

where the distance to shower axis  $r$  is in meters and  $\beta(\theta, S(1000))$  is given by

$$\beta(\theta, S(1000)) = \begin{cases} a + b(\sec\theta - 1), & \text{if } \sec\theta < 1.55 \\ a + b(\sec\theta - 1) + f(\sec\theta - 1)^2, & \text{if } \sec\theta > 1.55 \end{cases} \quad (3)$$

where  $a = 2.26 + 0.195\log(e)$ ,  $b = -0.98$ ,  $c = 0.37 - 0.51\sec\theta + 0.30\sec^2\theta$ ,  $d = 1.27 - 0.27\sec\theta + 0.08\sec^2\theta$ ,  $e = c(S(1000))^d$  and  $f = -0.9$ .  $S(1000)$  in Eqs. (2) and (3) is obtained from Eq. (1). Later, the signal assigned to each station is fluctuated using a Poissonian distribution whose mean is given by the *true* LDF. We impose typical values for trigger condition and saturation. Saturated detectors are excluded from the LDF fit.

Next, the lateral distribution of particles is fitted using a functional form given by

$$\log S(r) = a_1 + a_2 \left[ \log\left(\frac{r}{1000}\right) + \log\left(\frac{r+700}{1000+700}\right) \right], \quad (4)$$

where the slope of the LDF and the normalization constant are determined in each fit considering the core position as fixed in the reconstructed one. Finally, the reconstructed  $S(1000)$  is determined as the interpolated value from the fit at  $1000$  meters from the shower axis.

## 3 Energy and $X_{max}$ reconstruction

The method is based on MC parametrizations and, essentially, the energy of the primary and  $X_{max}$  are iteratively determined. As mentioned, the only ingredients needed are the reconstructed zenith angle of the incoming shower,  $\theta$ , and the interpolated  $S(1000)$  value from the LDF fit.

The iterative process should be started with an initial rough estimation of the energy. We arbitrarily use  $10$ ,  $20$  and  $50$  EeV. The results do not depend on this choice. Next,  $X_{max}$  is estimated using its average dependence on energy,

$$X_{max} = q_0 + q_1 \times \log_{10}(E_{prim}) \quad \text{g/cm}^2, \quad (5)$$

where  $E_{prim}$  is in EeV. Next, using  $S(1000)$  and  $\theta$ , primary energy could be obtained from

$$S(1000)/E_{prim} = p_0 \times \frac{1 + \frac{\Delta X - 100}{p_1}}{1 + \left(\frac{\Delta X - 100}{p_2}\right)^2} \quad \text{VEM/EeV}. \quad (6)$$

Then,  $E_{prim}$  obtained from Eq. (6), is used in Eq. (5) to get a new  $X_{max}$  following an iterative process until convergence is achieved (we set the convergence in energy at  $10^{-5}$ ). The convergence is always fast, only 3-6 steps are needed.

This method works properly in case of photon-initiated showers since  $S(1000)/E_{prim}$  vs.  $\Delta X$  shows an universal profile independently of primary energy due to the low fraction of muons in photon showers as explained before. However, hadron primaries produce EAS with a significant muon component and, in addition, the muon fraction depends on the primary energy. As consequence, if a global calibration curve is used, the inferred energy will show an energy dependent bias as shown in Fig. 1 (black points).

In order to account for the muonic component properly, different fits could be performed for each primary energy (Fig. 2). Then, the reconstructed energy obtained with the global

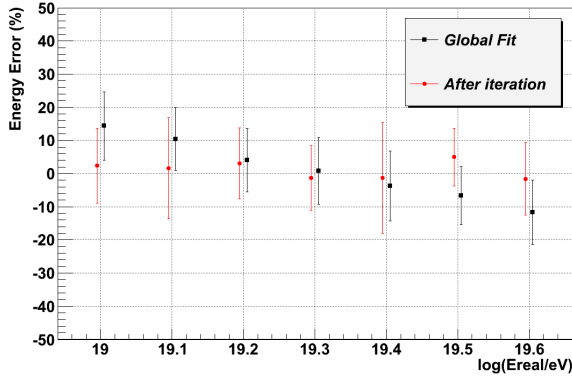


Figure 1: Energy error vs. primary energy for proton showers using their own calibration. The points and the error bars are the mean and sigma of the Gaussian fit to the energy error distribution respectively. Similar results for iron primaries.

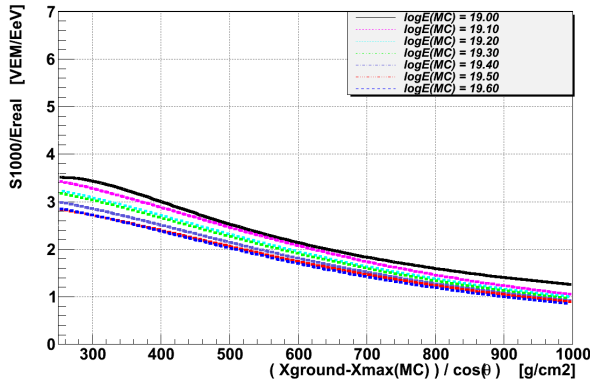


Figure 2:  $S(1000)/E$  vs  $\Delta X$  for proton showers. The fits corresponds to Eq. (6). Similar curves are obtained for iron showers.

fit could be used to select a new calibration curve from Fig. 2, repeating the process until the reconstructed energy is not modified. Only one or two iterations are needed. Thus, the energy bias is corrected (Fig. 1, red points) while resolution remains below 12% considering the whole simulations set.

On the other hand,  $X_{max}$  is also properly reconstructed. In fact, the bias is negligible and resolution is around 7% for proton and 4% for iron primaries respectively.

Obviously, it is impossible in practice to use different calibration curves for each primary. However, we could also calculate a *mixed* calibration fitting both type of primaries simultaneously (Fig. 3). The energy ( $X_{max}$ ) error is shown in Fig. 4 (Fig. 5). It remains below 10% (7%) for each primary and it is almost negligible if both are considered together. Resolution is better than 15% (7%).

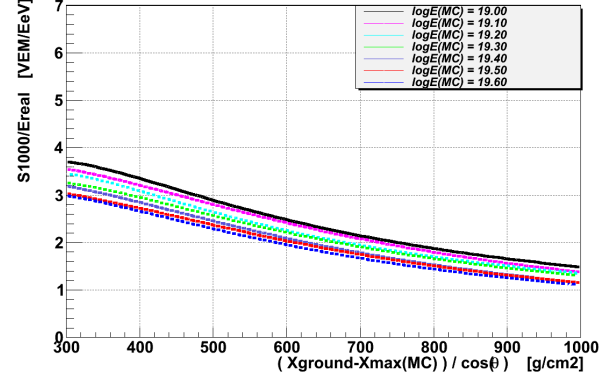


Figure 3: As Fig. 2 but mixing iron and proton primaries.

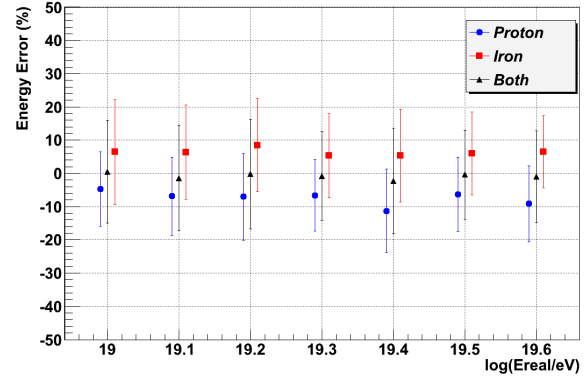


Figure 4: Energy error vs. primary energy for proton, iron and both primaries using the *mixed* calibration. The points and the error bars are the mean and sigma of the Gaussian fit to the energy error distribution respectively.

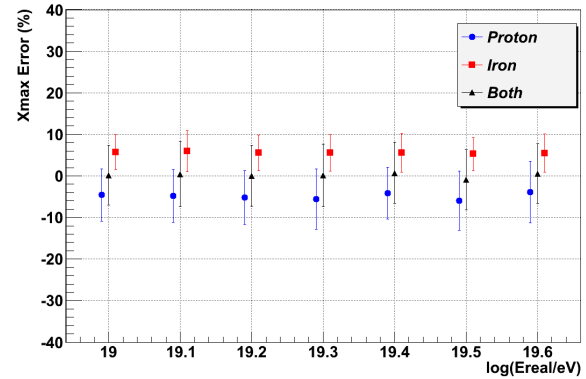


Figure 5: As Fig. 4 but for  $X_{max}$ .

Finally, we have determined the energy and  $X_{max}$  biases in case of a mixed composition sample. We have selected 100 samples with 100 events each. Proton and Iron primaries

are randomly included in the sample such the proton fraction varies from 0 to 1 in 0.1 steps. The energy ( $X_{max}$ ) bias as a function of the proton fraction is shown in Fig. 6 (Fig. 7). Using the *mixed* calibration, the energy ( $X_{max}$ ) bias varies from  $-7\%$  ( $-5\%$ ) to  $+6\%$  ( $+5\%$ ) as composition changes from pure proton to pure Iron.

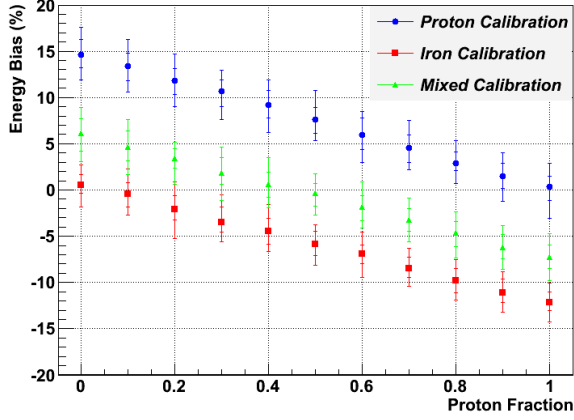


Figure 6: Energy bias as a function of the proton fraction using the three sets of calibration curves analyzed in this work. The points and the error bars are the median and the confidence levels at 68 and 95% respectively.

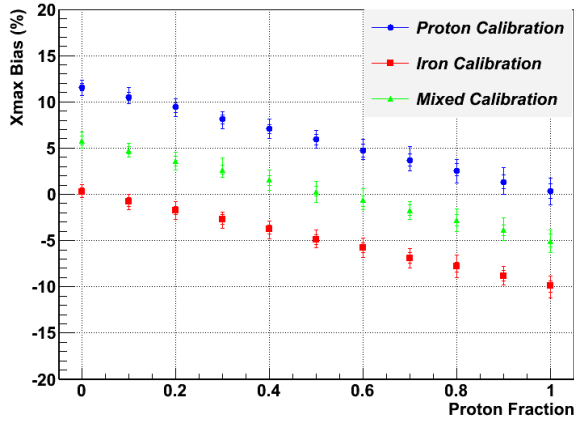


Figure 7: As Fig. 6 but for  $X_{max}$ .

## 4 Conclusions

An iterative method, previously developed to infer the primary energy of photon-induced showers in pure surface arrays, has been modified to be applicable to hadron-initiated showers. The inferred energy bias is negligible and the resolution is around 12% if each primary could be reconstructed with its own calibration. In a more realistic approach, the set of calibration curves have been also obtained mixing proton and Iron primaries and then, the bias

in the inferred energy varies from  $-7\%$  to  $+6\%$  as composition changes from pure proton to pure Iron, while resolution is better than 15%.

In addition, the method allows the indirect determination of the maximum of shower development,  $X_{max}$ , from pure surface data. The resolution achieved is around 7% and the bias goes from  $-5\%$  for pure proton to  $+5\%$  in case of pure Iron. Therefore,  $X_{max}$  could be estimated from surface data reliably, whose statistics are around 10 times larger than that from fluorescence telescopes. However, it is important to note that MC parametrizations could be affected by the fact that the simulations do not reproduce properly experimental data [18].

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